

Overview of General Electric's Advanced Turbine Systems Program

CONTRACT INFORMATION

Cooperative Agreement	DE-FC21-95MC31176
Contractor	General Electric Company 1 River Road Schenectady, NY 12345 (518) 385-2968 (518) 385-4314 FAX
Contractor Project Manager	Thomas F. Chance
Principal Investigators	Charles S. Cook Edward C. Lowe Roger W. Schonewald
DOE Project Manager	Kanwal Mahajan
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with GE Power Systems, 1 River Road, Schenectady,
NY 12345 (518) 385-2968

OBJECTIVES

GE Power Systems, with the support of the U. S. Department of Energy, has continued to design, develop and initiate the manufacture of its H class, gas turbine combined cycle power generation system. As stated previously (1), program goals remain consistent with the original overall DOE Advanced Turbine Systems goals of 60 percent combined cycle efficiency (LHV), <10 ppm NO_x emissions @ 15% O₂, and a 10 percent reduction in the cost of electricity relative to that provided by current technology. As originally constituted, the current Phase 3 of the utility scale ATS program was intended to allow DOE support of detailed gas turbine design, assessment of overall combined cycle system performance and, most importantly, allow test validation of component and subassembly designs, many of which have been severe technical challenges for the gas turbine industry and its suppliers.

APPROACH

GE Power Systems has been developing an extensively steam cooled gas turbine design which has evolved from early systems studies more than a decade ago. A large number of variations in cycle configuration were evaluated prior to settling on the current concept and starting to address its design challenges. As a result of having made a basic cycle configuration selection in advance of the initiation of the DOE ATS program, GE did not elect to participate in the ATS program until its selection for award in Phase 2 - Enabling Technologies. Through participation in Phase 2, GE was able to analytically and experimentally examine many of the critical technology issues associated with the use of closed circuit steam cooling in a very large, utility scale gas turbine combined cycle system. These technology issues included material steam compatibility, steam cleanliness requirements, heat transfer in steam cooled rotating components, combined cycle performance and system startup requirements.

The basic concepts of the GE steam cooled gas turbine design and overall combined cycle configuration have been discussed previously (1), (2) and are driven by the need to increase turbine inlet temperature to augment cycle efficiency and specific output while retaining a low enough combustor exit temperature to provide the required NO_x emission performance. The gas turbine can then operate as a parallel intermediate pressure reheater for the bottoming cycle and is fully integrated with the combined cycle's steam system. Heat rejected to the coolant in the gas turbine is directly transferred to the bottoming cycle rather than being lost to the gas turbine's exhaust.

PROJECT DESCRIPTION

GE Power Systems concluded negotiations for a Cooperative Agreement with DOE for Phase 3 of the ATS program allowing a program start in July, 1995 and started work on detailed design and component testing activities. A detailed work breakdown structure (WBS) shown previously (1) addresses both the 7H (60 Hz) and 9H (50 Hz) configurations of the ATS gas turbine combined cycle system. A large amount of commonality exists between the 60Hz and 50Hz versions of the gas turbine and the design of these components and subassemblies continues to be supported by the ATS

program. Proof of concept and subscale aerodynamic, heat transfer and material testing and evaluation are all generally common elements for both gas turbine designs and have been a part of the ATS program. Further, the overall operational strategy for starting, loading, unloading and unscheduled loss of load have been evaluated as a part of the ATS program and viewed as common to both single shaft combined cycle systems.

Earlier in 1997, the Department of Energy asked its utility scale ATS program participants for proposals for a potential revised ATS program which would eliminate the originally intended Phase 4 Commercial Demonstration phase. This phase was originally intended to provide DOE support for the construction and testing of a full scale, 60 Hz ATS combined cycle system at a U. S. utility site. Alternatively, DOE has indicated a willingness to restructure the current Phase 3 (Phase 3R) to potentially include the full speed, no load (FSNL) factory testing of the 60 Hz ATS gas turbine and GE has submitted a response to that request. It is expected that the restructured Phase 3 will be negotiated prior to the end of the current Phase 3 of the Cooperative Agreement.

RESULTS

Many of the system design considerations and results related to overall gas turbine configuration, startup and shutdown steam and air cooling issues and system performance have been discussed previously (1), (2) and will not be repeated here. Much of the effort during 1997 has been in continued validation of aerodynamic, heat transfer and material designs as well as continuing evaluation and improvement of casting yields for the single crystal nozzles and buckets required by the design.

Gas Turbine Description

GE's MS7001H gas turbines contain an 18-stage compressor, a can-annular DLN combustion system similar to prior GE gas turbines, and a 4-stage turbine. A 2600 F class firing temperature and closed circuit steam cooling are used in the turbine. A cross-section is shown in Figure 1. The compressor provides a 23:1 pressure ratio with 1230 pps airflow. It is derived from GE's high-pressure compressor used in the CF6-80C2 aircraft engine and Marine and Industrial LM6000 gas turbine. The MS9001H compressor has an airflow on 1510 pps.

The turbine employs closed-loop steam cooling of the first and second stage nozzles and buckets plus the stage 1 shroud. Steam from the combined cycle steam system is introduced into the turbine components, provides cooling, and is returned to the combined cycle for work extraction in the steam turbine. Air cooling is used for the third stage nozzles and buckets with the fourth stage being uncooled.

In the 1996 GE ATS-DOE paper (2), the development and validation activities behind GE's H gas turbine were described with focus on the compressor and stage 1 nozzle.

The paper described how GE is utilizing extensive design data and validation test programs to assure that a reliable H power plant is delivered to the customer. At that time the H compressor design approach had been validated by a successful Baseline compressor test program and, with the upcoming MS9001H and MS7001H compressor tests, the H compressors would be fully validated for commercial service. The H stage 1 nozzle design had been backed by extensive heat transfer tests, materials testing in steam, TBC testing, and steam purity tests. Test results had been integrated into detailed 3-d aero, thermal, and stress analyses. Final verification of the nozzle design was to be achieved through full size steam cooled nozzle cascade testing.

In the last year the MS9001H has continued to progress in design validation, design execution, and manufacturing of hardware for the first MS9001, which will be built and FSNL tested in Greenville, SC. during the second quarter of 1998. This paper will focus on the successfully completed compressor and nozzle cascade heat transfer tests and the "robust design" techniques being used to optimize designs.

MS9001H Compressor Test

Three separate compressor test vehicles are being utilized in the H compressor test program; a "Baseline" configuration, the MS9001H configuration, and the MS7001H configuration. Each test vehicle is CF6-80C2 size, approximately 1/3 scale of the H gas turbine's compressor. The "Baseline" compressor test, completed in 1995, validated the fundamental compressor design approach and was reported on in 1996 (2). This year the MS9001H compressor test was successfully completed validating the 9H compressor for production introduction.

Compressor Test Facility

The General Electric Aircraft Engine compressor development test facility, located in Lynn, MA, has been utilized to perform the H compressor tests. The facility consists of an enclosure "test tank", where the compressor rig is mounted. The rig is driven by a 33,000 horsepower steam turbine that can drive the compressor rig up to a speed of 15,000 RPM. The test tank is connected to plenum tank that supplies undistorted air flow to the compressor rig. The inlet air pressure is controlled via control valves upstream of the inlet plenum. The discharge is connected to six (6) airflow measuring venturies that are individually controlled to accommodate air flow measurement requirements. Air flow is also measured with the bell mouth attached to the inlet of the compressor rig. The exhaust, or back pressure, is controlled with a discharge control valve located immediately down stream of the compressor rig and ahead of the venturies. Bleed flows are discharged to the atmosphere, controlled by valves, and measured with a venturi in each bleed pipe.

A computerized data acquisition system is used for data reduction and real time monitoring. The unit can scan over 2,000 performance parameters at 40 times per second, making data available for continuous real time monitoring programs. More than 1300 pieces of instrumentation were used on the MS9001H compressor test to

measure aerodynamic, aeromechanic, and thermal characteristics of the compressor.

MS9001H Compressor Test Results

The MS9001 compressor provides 1510 pps of airflow at a 23:1 pressure ratio. This scales to 158 pps and 23:1 pressure ratio for the test rig. Test objectives included performance, operability, stall margin, and aeromechanics. The rig was tested for more than 160 hours with more than 500 test points recorded.

The compressor test results were excellent. As shown in Figure 2, a plot of compressor adiabatic efficiency as a function of airflow, the compressor demonstrated design point airflow 1.9% above target and design point efficiency 0.2 points above target. Power turndown performance and operability testing were successfully conducted with airflow turndown capability exceeding the 40% target. All of the compressor vibratory stresses were within allowable limits.

An important part of the test was establishment of the high speed compressor map shown in Figure 3. In addition, testing was used to validate the no load operating line, full load operating line, and stall margin. Start testing was performed to validate starting characteristics on the operating line and on a 10% high operating line

The 9H compressor has been built upon a foundation of successful CF6-80C2 operation and validated by compressor testing. Similar results are expected for the MS7001H tests which will run in 1999.

Stage 1 Nozzle Cascade Test

The H stage 1 nozzle has been designed using design data and validation tests for heat transfer, material capability, and steam cooling effects. Test results have been incorporated into detailed 3-d aero, thermal, and stress models to show that the H stage 1 nozzle meets life requirements. As further validation, actual full size prototype, steam cooled, stage 1 nozzle segments are being tested at H thermal conditions. This is accomplished by mounting two nozzle segments in a test stand behind a Dry Low NO_x (DLN) combustion system and transition piece as shown in Figures 4 and 5. A GE Aircraft Engine test facility located in Cincinnati, OH is being utilized to perform testing. The facility provides pressurized air at appropriate temperature to the test stand. A single can combustor and transition piece is used to burn natural gas and provide two nozzle segments with the H gas turbine level inlet temperature. A separate steam supply is used to provide cooling to the nozzles.

The nozzles being used in the testing are of a prototype configuration which does not include all of the producibility and design improvements incorporated into the product design. However, the prototype configuration does use the same single crystal N5 material and the same fundamental cooling concepts as the product. This makes the prototype an excellent tool for obtaining early test evaluation of the thermal and cyclic characteristics of steam cooled nozzles at H operating temperatures.

In 1997, the Heat Transfer phase of the test program was successfully completed, verifying that pretest nozzle thermal objectives were attained and correlating detailed 3-d thermal analyses of the nozzle. The nozzles used in the testing are shown in Figure 6. The two nozzle segments contained 180 pieces of instrumentation; primarily thermocouples for metal temperature distribution and pressure taps for steam circuit flow monitoring. Testing consisted of more than thirty steady state data points over a range of nozzle inlet temperatures. Figure 7 shows nozzle leading edge temperature data, which closely matched the pre-test prediction, as a function of inlet temperature. Figure 8 shows the design point distribution of temperatures around one span location. Results, shown compared to the prediction, are at or below the prediction. The detailed results from all of the thermocouples are being correlated with the analytical model.

Since the completion of the heat transfer testing, the test rig has been configured with new prototype nozzle segments containing significantly less instrumentation. These parts will be operated through a cyclic test operation to simulate field operation for correlation with the low cycle fatigue (LCF) analyses.

“Robust” Design

The development of GE’s H program has required development of improved GE and vendor manufacturing processes in key areas such as IN718 forging, single crystal turbine airfoil castings, and TBC coatings. Rather than just relying on manufacturing improvements in process capability, GE is also addressing the design implication on manufacturing requirements through a series of design tools called “Robust Design”. Part of GE’s drive for improved quality through its Six Sigma program, “Robust Design” tools are used to optimize part requirements and reduce the sensitivity of key part requirements (such as life) to variabilities such as manufacturing process tolerances.

An example of the use of “Robust Design” techniques on the H program is the design of the stage 1 nozzle. The nozzle’s part life was identified as the Critical to Quality (CTQ) key performance characteristic. The part’s geometric nominal dimensions were identified as the Key Control Parameters (KCP), and the manufacturing geometric tolerances identified as the Key Noise Parameters (KNP). Using this information, a Design of Experiments (DOE) was created to be performed on the 30,000 node 3-d solid finite element model of the stage 1 nozzle. The DOE array was designed to have 5-levels for each control parameter so as to capture the nonlinear dependence of the LCF life on the KCP’s. The LCF life data for various combinations of control and noise parameters was analyzed to compute statistical means and variances of the LCF life at various points, such as finite element nodes, of interest. These results were then used to generate response surfaces of means as well as variances which were then used in conjunction with numerical optimization to determine the optimal values of control parameters. Figure 9 shows the results. The statistical means of the LCF life meet design requirements and are about the same for both cases. However, with the same manufacturing tolerances, the results show less standard deviation. The result

is that the phase II design is more robust with respect to manufacturing tolerances. This allows the flexibility to either maintain the reduced sensitivity of the design or to relax selected tolerances to improve the part producibility and/or process yield.

CONCLUSIONS

GE is continuing on its path to introduce the H product line providing the customer with the highest thermal efficiency, lowest cost of electricity option for future power generation. The successful compressor rig test and nozzle cascade heat transfer test are key milestones on that path. The components have been designed using the latest “Robust” design techniques. Hardware is being completed and delivered to GE’s plant in Greenville, SC, and preparations are on track for FSNL testing of the first MS9001H gas turbine in 1998. The MS7001H will follow with FSNL testing in 1999.

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GE Power Systems, Schenectady, NY:

Michael James
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Viran Kumar

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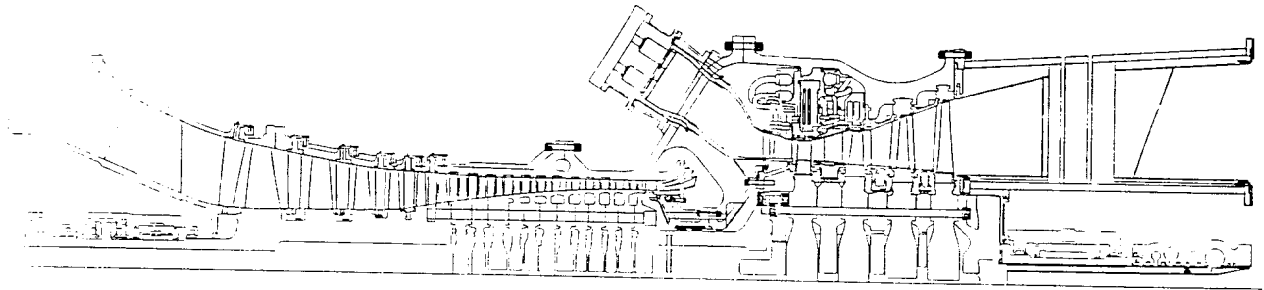


Figure 1 - 7H Gas Turbine

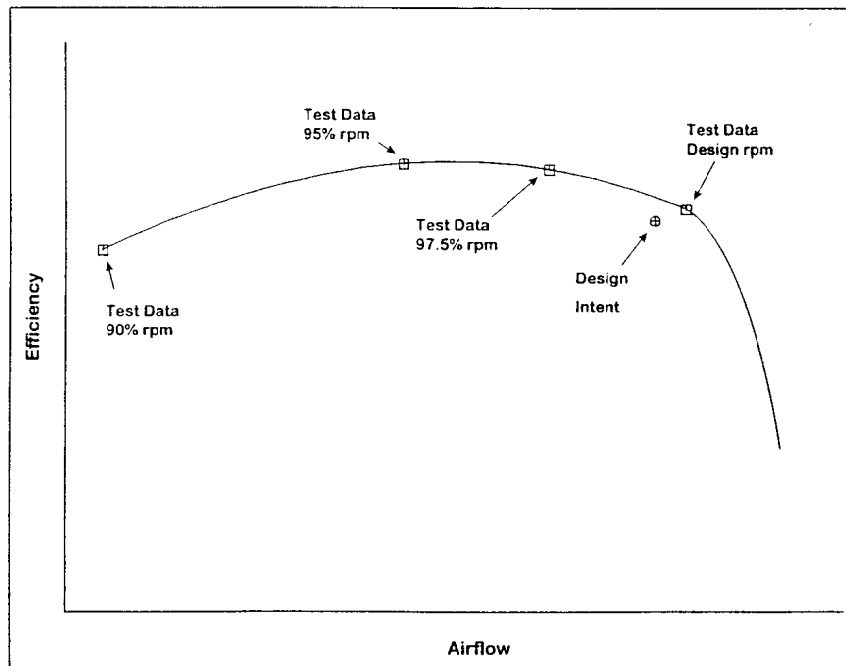


Figure 2 - 9H Compressor Test Efficiency vs Airflow Exceeds Design Objectives

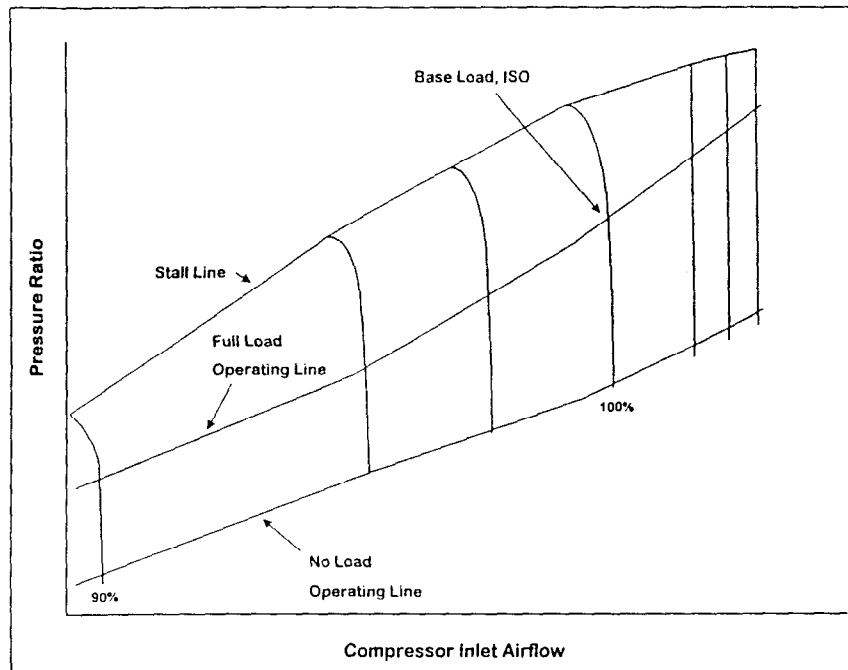


Figure 3 - 9H Compressor Test Validates High Speed Compressor Map

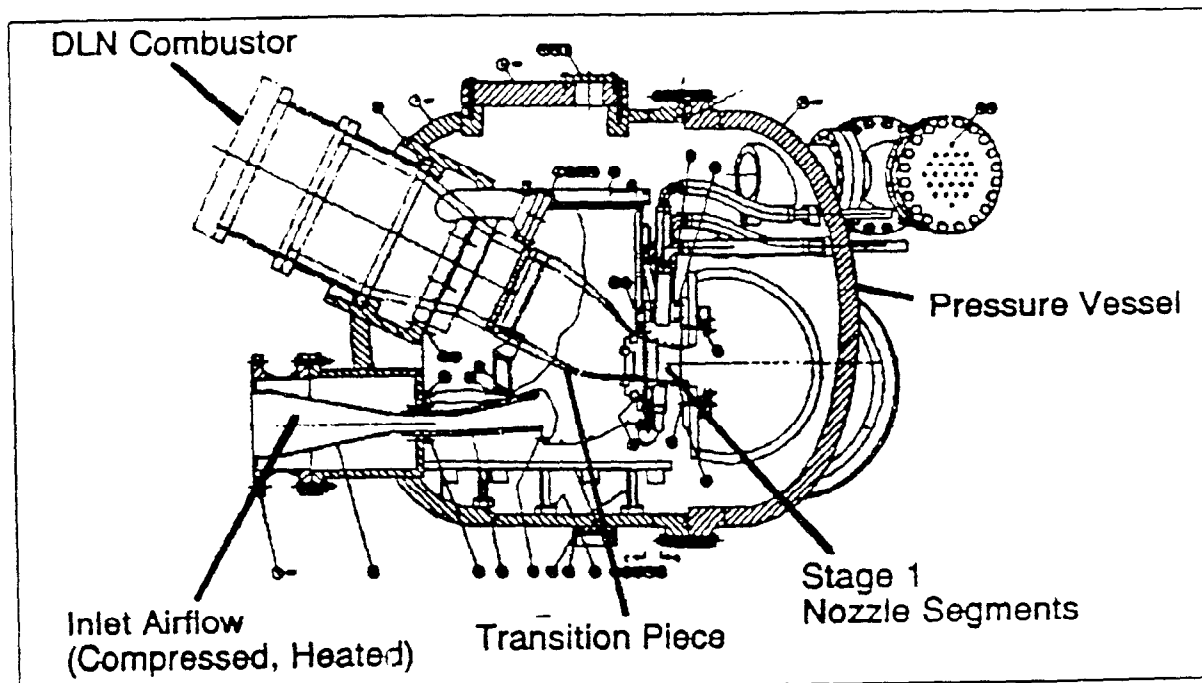


Figure 4 - Stage 1 Nozzle Cascade Test Stand

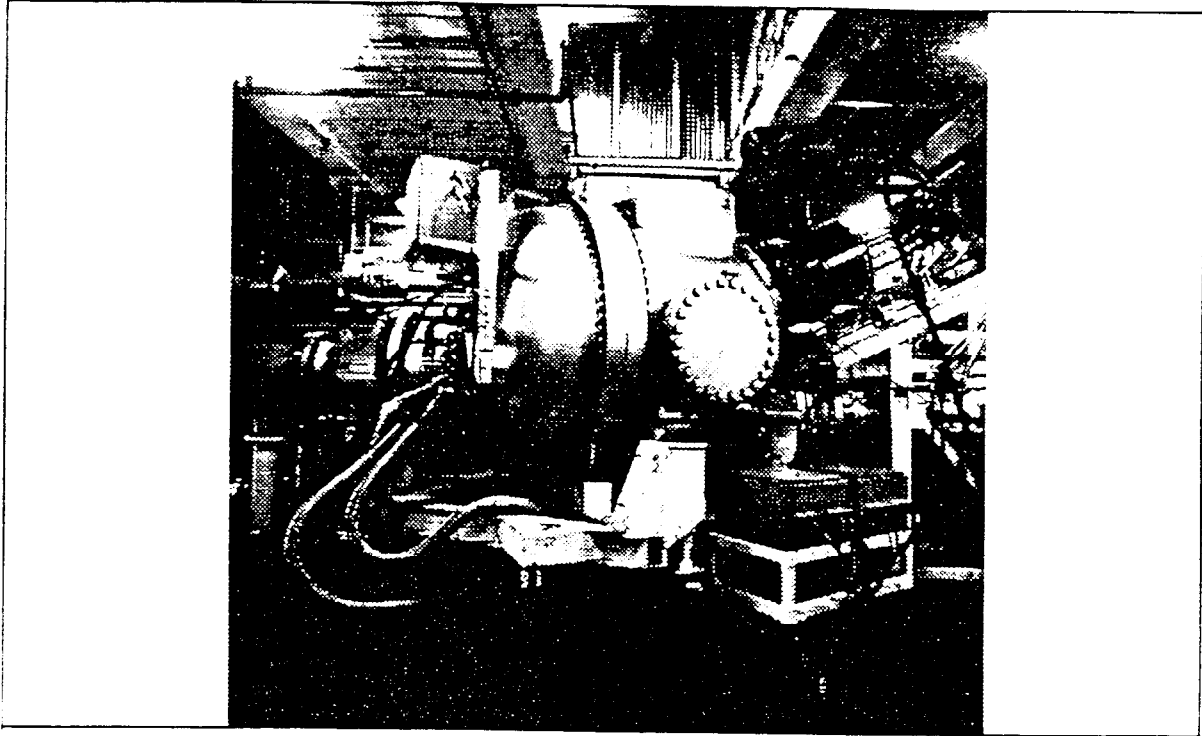


Figure 5 - Stage 1 Nozzle Cascade Test Stand



Figure 6 - Stage 1 Nozzles Used in Nozzle Cascade Heat Transfer Test

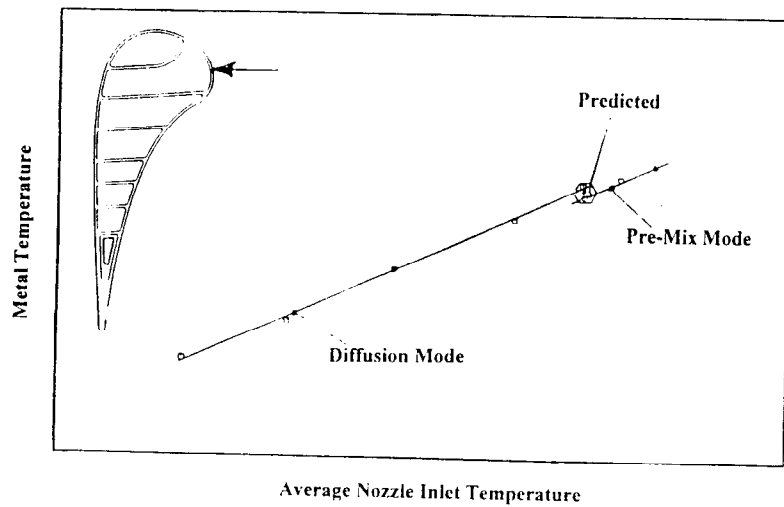


Figure 7 - Nozzle Cascade Leading Edge Temperature Consistent With Predictions

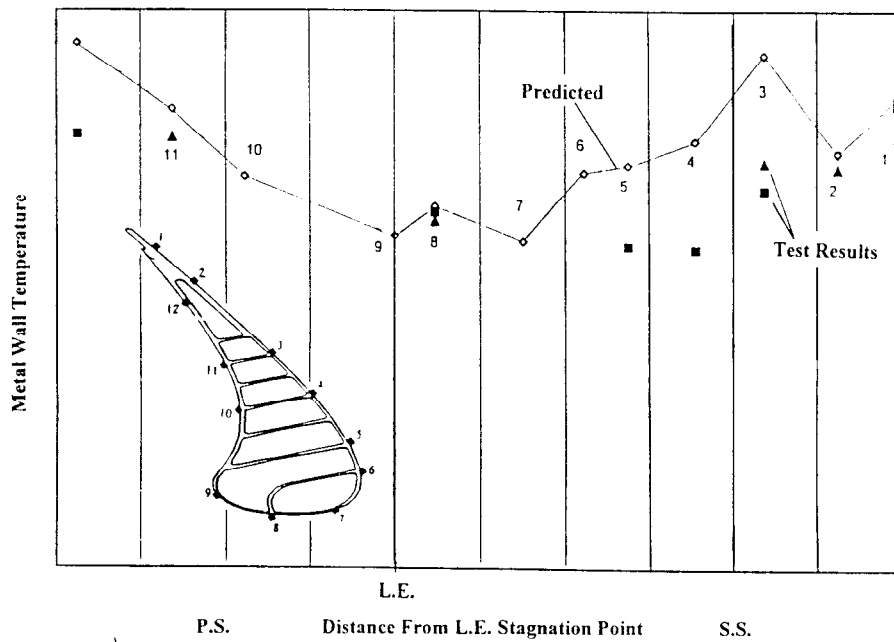


Figure 8 - Nozzle Cascade Airfoil Temperature Distribution At or Below Prediction

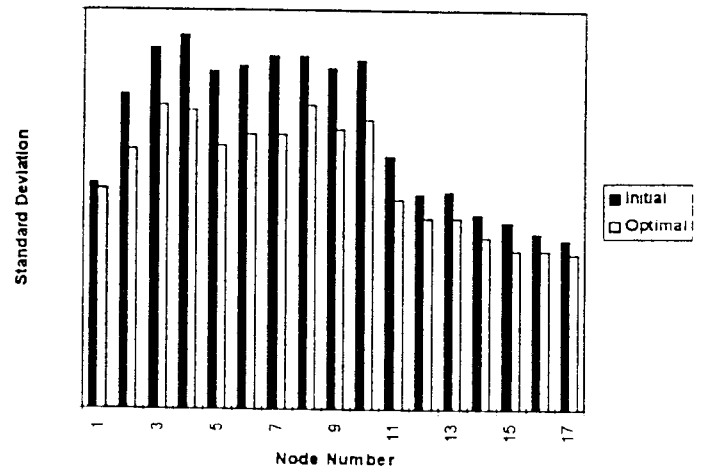
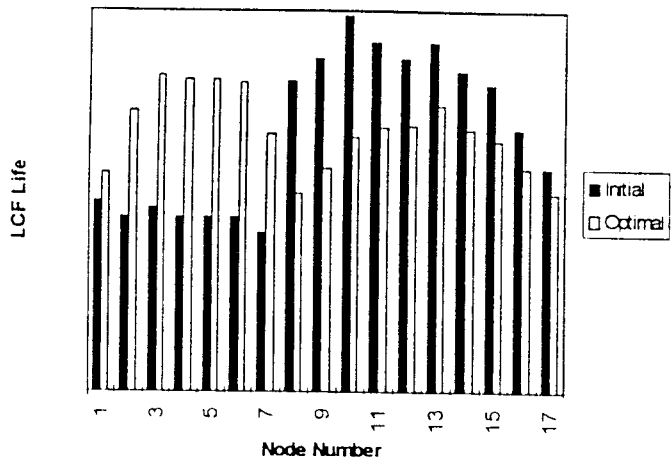


Figure 9 - "Robust Design" Results In Less Deviation For The Same Manufacturing Tolerances